Chapter X

INFRASTRUCTURE AND CAPABILITIES OF A NEAR REAL-TIME METEOROLOGICAL AND OCEANOGRAPHIC *IN SITU* INSTRUMENTED ARRAY, AND ITS ROLE IN MARINE ENVIRONMENTAL DECISION SUPPORT

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1. Introduction

The mission of the U.S. National Oceanic and Atmospheric Administration (NOAA) is to understand, predict, and monitor the oceans, coasts, fisheries, and atmosphere. NOAA also participates in the U.S. Coral Reef Task Force created under U.S. Presidential Executive Order 13089 (June 11, 1998, Office of the White House Press Secretary), whose mission is to utilize the combined U.S. governmental agencies to preserve and protect U.S. coral reefs. Although there are many efforts afoot across the globe to increase the breadth of meteorological and oceanographic monitoring networks (e.g., see National Research Council, 2003; U.S. Commission on Ocean Policy, 2005; NOAA Observing System Architecture, 2005; Global Observing Systems Information Center, 2005), few are deployed specifically to monitor coral reef areas, and none contain the information synthesis capabilities and instrumentation designed to monitor coral health directly in near real-time, except as described in this chapter.

1.1 OVERVIEW OF MONITORING STATIONS

Most meteorological and oceanographic monitoring stations have certain common characteristics:

- Measurements are made for air temperature, wind direction, wind speed, wind gusts and barometric pressure. Additional instruments may measure sea temperature, dew point, rainfall, photosynthetically available radiation (PAR) or wave height and period.

- The measurements are usually averaged over a period of one hour and broadcast via a satellite relay (e.g., GOES, Argos or Iridium) or high-frequency radio, and then to a World-WideWeb (“Web”) site where the data can be viewed, often in near real-time (see below for further explanation).

- The stations in the network are designed to receive very little maintenance, as the sites are remote and labor is expensive. Instruments requiring high maintenance are not included for these reasons.

In: *Remote Sensing of Aquatic Coastal Ecosystem Processes,*
Laurie L. Richardson & Ellsworth Frank leDrew
Kluwer Academic Publishers, 2005 (draft)

- There are usually Web-based databases or other mechanisms for retrieving the historical raw data, or quality-controlled data, or both.

- The data are primarily used by weather-predicting agencies to form local and long-range forecasts, and to assist in advising mariners of existing or predicted sea state.

A relatively new application of the technology that led to the development and support of meteorological monitoring stations is deployment of oceanographic monitoring stations that include in-water measurements in addition to the above parameters. Such stations have also been developed for near-shore coastal zones. The newest generation of in-water monitoring stations now provides specific data related to biological processes and stress responses, thus expanding this technology from monitoring of the environment to scientifically based predictive and diagnostic capabilities.

We have been actively involved in the design, construction, deployment, and expansion of near shore (coastal) marine diagnostic and predictive monitoring arrays. This chapter will provide an overview of the current capabilities of our system, and an example of the use of this capability to study aquatic ecosystem processes in a coastal (coral reef) environment.

2. Challenges in Setting up a Network

A number of specific issues and challenges must be addressed before setting up an *in situ* meteorological and oceanographic instrument array. Some of the common and significant problems to setting up a data collection network include the following:

- The financial outlay to construct just one station can be over US $100,000 (but price depends upon many factors). This includes the cost of the instruments, replacements of those instruments, instrument calibrations, travel and transportation costs, diving support, etc.

- In the U.S.A., permission must be received from the U.S. Coast Guard, the Army Corps of Engineers, the local Fish and Wildlife Service, and possibly the local Marine Protected Area (MPA) to construct the station. Such permission may be extremely difficult to come by and may require numerous permits, with long time lags in between application and award of the permit.

- If the site is very remote, the data must be sent via satellite. This requires subscribing to an available and appropriate satellite, then implementing a data retrieval system.

- The cost of field support for technicians is appreciable when you consider salaries, boats, trailers, fuel, insurance, supplies, and other unforeseen costs.

One of the chief disadvantages these stations and networks have is that instruments that malfunction or start to exhibit drift (i.e., begin to record an increasing disparity between true and measured values) cannot be attended to in a timely (i.e., days or weeks) fashion. Another problem is that incoming data in essence "stack up" and are not reviewed in a timely fashion; hence, features of interest may be missed by scientists or MPA managers. We describe below the way in which we have addressed such problems for one particular network. Included is a summary of our current effort to make use of the data collection capabilities of our system to provide a new capability for understanding coral health from afar.

3. The CREWS Network

The Coral Reef Early Warning System (CREWS) network is being developed through the Coral Reef Conservation Program (CRCP) of the National Oceanic and Atmospheric Administration (NOAA) in response to a U.S. Coral Reef Task Force (established through Executive Order 13089) recommendation to install a network of meteorological and oceanographic monitoring stations at all major U.S. coral reef areas (e.g., the Florida Keys, the Bahamas, Hawaii, U.S. Virgin Islands, Puerto Rico, American Samoa, etc.) by 2010. The stations are being constructed and deployed by the Atlantic Oceanographic and Meteorological Laboratory (AOML) in Miami, Florida, and the Coral Reef Ecosystem Division (CRED) in Honolulu, Hawaii. AOML constructs and installs fixed pylon-type stations, and CRED deploys buoys. Other stations providing data to the network are the SEAKEYS Network of seven stations in the Florida Keys (Ogden et al 1994) and the Australian Institute of Marine Science (AIMS) Weather Station Network (http://www.aims.gov.au).

The basic purpose of the CREWS network is to compile long-term data sets upon which MPA managers can be aided in their management decisions, and upon which researchers can determine yearly patterns and trends. CREWS stations (Figure 1) measure wind speeds and gusts, wind direction, air temperature, sea temperature, salinity, PAR, and discrete or broadband ultraviolet radiation (UVR). Oceanographic instruments normally require frequent (every ten days to two weeks) maintenance to prevent biofouling and consequent drift or failure of the instrument. However, because of this level of maintenance, together with the data monitoring software described below, high confidence is attained in the quality of data, and very timely use can be made of the data in the way of an inference engine or expert system (artificial intelligence tool) shell.

We describe below the various operational and scientific aspects of the AOML fixed pylon-type stations ("CREWS stations").

4. Station Construction and Deployment

The construction and deployment of CREWS stations involves some formidable and oftentimes lengthy tasks. Table 1 presents a basic list of phases and tasks, while Figure 2 shows a Gantt chart detailing a typical sequence of events involved in the entire process. Although this is not the place to describe each of the phases in depth, a brief discussion of some of the considerations involved in site selection will provide an insight into the follow-up activities that are required in setting up the station.

4.1 SITE SELECTION

It would seem obvious that the best place to put up a coral reef meteorological and oceanographic monitoring station would be near a coral reef, but there are in fact many considerations that must be taken into account. Adhering to the same principals of site selection for each station allows for comparison among the stations, which provides for greater confidence in conclusions. Following are some of the considerations that must be taken into account before choosing a proper site for installing a CREWS station.

- It is best if the site can be on the lee side of the island or local land mass (that is, away from the prevailing winds), but not so close to land so that wind speed and direction cannot be measured to show the general trend throughout the day. The concept is that it would be best not to set up where the station would continuously be pounded by high seas. Not only would this reduce the lifetime of the station, but it would also make it very difficult for personnel to carry out the installation and maintenance. It should be paramount to keep safety of the station maintainer at the top of the list of station considerations.

- The site must be acceptable to NOAA's Coastal Zone Management office, any National Park or Reserve where the station might be located, the Army Corps of Engineers, the U.S. Coast Guard, the U.S. Fish and Wildlife Service, and/or any other appropriate regulatory agency.

- Arrangements must be made with a local entity or person for station maintenance. Ideally, a graduate student or federal or territorial agency partner would see to the maintenance every ten days to two weeks. The upkeep is generally low effort, but maintenance and calibration costs should be carefully determined and an agreement made with the local maintainer on who will pay for specific costs.

- Because of the design of the station, the site should be in 6 m of water. This is especially important for comparison of data from the same research instrument suite deployed at different sites. "Colonized pavement" (NOAA Biogeography Program, 2005) bottom seems to be best for the CREWS station deployment, as it provides for comparisons of similar coral community types at all the regions of installation. Placing the station at an area where extensive research (e.g., coral bleaching) has been conducted before is helpful, especially since the extended research instrument platform contains instruments designed to answer research-related questions.

- The station will ideally not be at a site where it could be considered visually obtrusive or offensive in any other way to the local population. With community involvement, the local population can be educated as to the benefits of the station, and, if applicable, informed that the station location is temporary.

- It would be highly advantageous if the site were at a spot where an interested party could see it often, to help obviate possible vandalism. (Hopefully this and the above conditions go together.)

- In cases where a Web camera is operating (see Figure 3), it would be advantageous if the station were within line-of-sight of an area on shore where the microwave receiver dish could be located. The local receiving dish would relay real-time viewing of the reef below on the observation monitor, and, if desired, that signal could go out as an Internet image stream.

- The station would preferably not be in an area experiencing high tidal range and/or high tidal or other currents. This is for diver and maintainer safety, as well as for the integrity of the station.

- If the station can serve as a navigational aid, this would help bring extra value of the station to the local population.

5. Station Maintenance

The goals of station maintenance are to assure that the highest quality data are collected and delivered, and to prevent the CREWS pylon from significantly altering the environment it is monitoring. Because of the high probability of biofouling and drift of oceanographic instruments, it is essential that the stations receive at least some attention every ten days to two weeks, primarily to reduce biofouling. Thus, it is critical for the CREWS Network to have local cooperating field technicians or scientists at each locale where the stations are deployed. In many cases, utilizing a graduate student to perform the maintenance operations has benefits for both parties: the student receives a stipend, or other support, and gets what he or she knows first hand is good quality data for their thesis/dissertation research; and the station owner gets the required attention to the immediacies of station operation as required.

6. Data Validation

Successful interpretation of the incoming near-real time data by either experts or expert system software (see Information Systems, below) is dependent on the quality of the incoming data. In particular, in remote locations, with sensors chosen for long-term stability and dependability, recorded values for many parameters may experience drift. Automated expert system evaluation can identify suspect data after it has been produced; however, it is necessary for establishing quality of the long-term data set to periodically validate the data. These validations are performed by comparison of the *in situ* sensors that have been exposed to the environment for extended periods against recently calibrated instruments maintained and stored in a clean, controlled environment. Validation of a standard CREWS station includes intercomparison of the wind sensor data and verification of the quality of the conductivity-temperature-depth (CTD) data. The wind sensor data can be monitored for self-consistency and against local weather reports remotely. The CTD, on the other hand, requires a local technician to visit the station for a calibration check.

Validating CTD sensors on the CREWS stations is made by comparison of the CTD values from the station, as reported to the CREWS Web site, with readings from a calibrated portable CTD at the station. To perform a validation the maintainer will need a recently calibrated high-precision CTD, a (preferably) waterproof or water resistant laptop computer with an RS-232 interface, CTD processing software, an RS-232 communication cable, and access to the Web to see the currently reporting values. Validation is done both before and after a simple in-water cleaning process, consisting of including wiping down the sensor surfaces with a soft cloth, to ascertain the effect of biofouling or other contaminants on the measurements. Since the reported values are hourly averages of six discrete data points, the calibration CTD will need to be operated on the same sampling schedule. Validation measurements should be collected for two time periods before and two time periods after cleaning, so the total calibration time, including the cleaning dive, is approximately five hours. It is possible for approved divers to use the calibration time to enter the water to clean and inspect the mooring and supporting hardware for signs of wear. If the CREWS station CTD is found to be out of calibration, it is removed and replaced with the calibrated CTD. The field CTD that was removed would then be returned for cleaning and calibration. Maintainers should follow this validation process at least once every two weeks.

7. Information Systems

7.1 PRESENTATION OF REAL-TIME RAW DATA

At the station each instrument sends data (or is polled by a data logger), which averages the number of readings over the hour and then transmits a stream of numbers ("datastream") up to a GOES satellite. The datastream is then relayed to Wallups Island, Virginia, and then to AOML (see Figure 4). Individual sensor values are then parsed from the datastream and presented as near real-time values on the CREWS Web Page (http://www.coral.noaa.gov/crews), with the disclaimer that the data should only be considered as provisional since they have not yet been reviewed. The disclaimer is necessary because mariners and others who are trying to make decisions based on the data should keep in mind that the data might be wrong (e.g., through data drift or other mechanical problem), and to thus make their decisions carefully. However, because of the CREWS suite of expert systems, notice is usually given automatically when data look suspect, and the maintainer is usually able to attend to a failing or drifting instrument in a timely fashion.

7.2 DATA QUALITY CONTROL

After the data have been parsed from the raw data stream, data quality control personnel receive files of the raw data. The files are reviewed and edited in an attempt to remove unreliable numbers. Generally speaking, data are accepted if they fall within a range of expected, ambient values that are determined from trends of previously received data, personal experience, and the published literature. For example, sea surface temperatures (SST) in the Caribbean are expected to be in the range of 26-32^{o} C during summer months, whereas SST values of 18-24^{o} C are normal for winter months. Care must be exercised when determining ranges, given that these vary from location to location. The CREWS expert system software reviews data for appropriate ranges as they arrive (see below), but follow-up screening by a data quality specialist ensures the quality of the data before archiving in the CREWS Integrated Monitoring Network (see Figure 5).

Completeness reports are compiled for each station for each year and are included in metadata reports. Completeness reports list the availability of each parameter for that year. For example, if salinity readings are not available this is noted indicating over the range (in days) for which values do not exist. Once the completeness report is finished, metadata files are then emailed to and stored by NOAA's Coral Reef

Information System (CoRIS). Annual data files are then uploaded to the CREWS Web site where they are accessed by the general public.

7.3 EXPERT SYSTEM ANALYSIS

The underlying structure of the expert system has been previously described in Hendee (1998, 2000). Production rules (basically, if/then-type heuristics) utilized in CREWS are drawn from published data, field observations, and from discussions in the literature.

The approach presented here reflects first-order laboratory and field-based testing of instruments, in conjunction with programming of the expert system. The expert system acts as a model, which will eventually help to further elucidate the role of the physical environment in biological events which are influenced by the physical environment, and which can be measured with a robust sensor.

Table 2 presents the terms used for the inference engine within the expert system. Basically, these subjective interpretations help to reduce complexity in modeling the environment and in assessing its role in influencing a marine behavioral event (e.g., coral bleaching). Data from each sensor are categorized according to the table into *subjective data ranges* (e.g., drastically low, very low, etc.), as described by experts who use the sensors or work with the parameters in question. The terms “unbelievably low” or “unbelievably high” represent thresholds beyond which the measurements would be considered unrealistic in nature. The *subjective periods of the day* explained in Table 2 are those perceived by humans, and which also quite often correspond to periods of biotic behavior (e.g., crepuscular feeding behavior at “dawn” or “sunset”). When an observed condition (e.g., high sea temperature) holds to the same subjective data range beyond one of the basic periods, which are three hours each, the condition is reassigned to the next larger category. For instance, if sea temperature is “very high” for “dawn” and “morning” (each of which is a three hour period) it becomes reassigned as “dawn-morning,” a six hour period. Similarly, if the high sea temperatures persist for all daylight hours, the condition is reassigned as occurring for “daylight-hours.”

8. Research Application

The CREWS stations have been designed to provide an extensible architecture so that instrumentation may be added relatively easily to provide answers to selected research questions. One of the primary goals of the CREWS stations has been to elucidate the role of light and temperature in the phenomenon of coral bleaching. Another research question of value is determining what role carbon dioxide flux plays in coral growth, bleaching, and coral larval settlement. In select situations, where sediment resuspension and turbid outflow may have deleterious effects on the coral reef, turbidity sensors might also be added. The list of possible research questions that can be addressed by quality long term investigation of specific parameters includes, in addition to the above mentioned parameters, monitoring of nutrients, dissolved oxygen, pH (potential hydrogen), Eh (electrochemical potential), and video-based ecosystem analysis. For the present discussion, research into the role of light and high sea temperature in coral bleaching events will serve as an example of the effectiveness of the CREWS station design and expert system analysis.

8.1 CORAL BLEACHING

Coral bleaching may be described as the general whitening of coral colonies due to the loss of symbiotic zooxanthellae from coral tissues and/or a reduction in the densities of zooxanthellae and photosynthetic pigment concentrations within the zooxanthellae (Glynn 1993). Typically, bleaching is a response to environmental stressors including extreme water temperature (Fitt, et al. 2001, Saxby, et al. 2003), intense light (Anderson, et al. 2001), or biological factors such as infection by bleaching-inducing bacteria (Sutherland, et al. 2004). Intense coral bleaching may result in extensive mortality of reef-building corals and a reduction in the growth rate of surviving colonies. A further consequence is the loss of production of calcareous substrate (the reef framework) necessary to support the abundance and variety of reef-dwelling and reef-dependent aquatic life. Interestingly, scientists have discovered that corals live in environments that are very close to the limit in which they can survive with respect to temperature, insolation, and even pH. A water temperature increase above a selected coral's upper thermal tolerance of 1 to 2^{o}C for two weeks has been accepted as a rough heuristic for coral bleaching. This temperature range is quite close to the upper limit that the coral normally experience (Coles and Jokiel 1976).

It is known that not all corals, even of the same species, will exhibit signs of coral bleaching over their entire surface under the conditions of thermal stress described above. In addition to temperature stress, increases in the duration and intensity of light exposure beyond the range of photoacclimatization has shown a strong correlation with the coral bleaching response (Shick et al. 1996, Hoegh-Guldberg 1999, Lesser and Farrell 2004). It is believed that the combination of high temperature combined with increased insolation in surface waters leads to coral bleaching, and that the areas of corals of the same species and symbiotic (zooxanthellate) clade that do not bleach are perhaps not exposed to equivalent amounts of sunlight. The intensity of light on the surface could be limited locally by physical shading, as in the bottom surfaces of corals as opposed to the tops, or due to UVR screening substances. These include chromophoric dissolved organic matter (CDOM) in the water column or mycosporine-like amino acids within the coral itself (Lesser and Farrell 2004, Otis, et al. 2004).

In order to gain an understanding of the role of light in coral bleaching, it is necessary to determine the spectra and intensity of light at the coral surface. Providing individual light sensors at each coral in a study region is prohibitively expensive and may disrupt the environment. Therefore, an approach taken by the CREWS research team has been to calculate coral light exposure by extrapolating from CREWS station irradiance data.

8.1.1 *Remote verification of coral bleaching alerts and predictions*

One method we have developed to verify our coral bleaching alerts and predictions has been to install an underwater camera that can transmit images locally to a shore-based station and then to the Web. The underwater Coral Camera infrastructure at St. Croix (Figure 3) is composed of two cameras (above and below water) and a Niagara™ streaming video computer server (which encodes the signal from analog to digital) located on shore, and also at AOML. The above-water camera, located on shore and pointing directly at the CREWS station, is connected to a video server inside a building. This camera is a manual zoom camera mounted in an industrial-strength all-weather housing within direct line-of-sight of the station. The second camera is located underwater and tethered to the CREWS station in such a manner that a diver is able to move the camera to different viewing locations around the CREWS station, to as far away as approximately 150 m, and down to a depth of 20 m. The camera is powered by the central station's solar-powered batteries and is in communication with the onshore video server via a microwave link, consisting of a transmitter on the station and a receiver onshore. Once the video signal is processed and converted into Windows Media™ by the encoder, the signal is then prepared for streaming over the Internet. This is possible only via an Internet Virtual Private Network (VPN) link between St. Croix and AOML, since security is of paramount concern for all federal installations. When an Internet user wishes to view the video stream, a request is sent to the AOML based server. The server in turn creates a link over the VPN to the video server in St. Croix. The server then packages the video stream and provides it to the Internet requestor. In this way, after CREWS initiates bleaching alerts for St. Croix, a user can look to the underwater Coral Camera to see if, indeed, bleaching is taking place. Since different species bleach before others, however, it is of course important to position the camera to point at the species of interest.

8.1.2 *The Underwater Light Field*

The wavelength dependence of biological responses to light is well established. The relationship varies from the induction of photosynthetic activity by PAR (400 – 700 nm) to the induction of repair enzymes (or production of UVR-screening pigments) during exposure to component bands of ultraviolet–A radiation (UV-A, 315 – 400 nm) (Corredor, et al. 2000) or to direct photochemical damage to DNA by ultraviolet–B radiation (UV-B, 280 – 315 nm) (Lyons, et al. 1998). Due to the complexity of coral responses to light, a number of studies aimed at investigating the relationship between different spectral regions and coral bleaching have been undertaken (Gleason and Wellington 1993, Fitt and Warner 1995). In these studies, both the density of zooxanthellae cells and the concentration of chlorophyll in zooxanthellae showed significant reductions with increasing UVR and visible light intensity.

UV and blue light penetration in shallow oligotrophic environments, with chlorophyll *a* concentrations of less than 0.5 mg/m^3, is largely controlled by CDOM (Markager and Vincent 2000, Nelson and Siegel 2002). This macromolecular mixture of organic molecules contains a complex array of unidentified chromophores with overlapping absorbance spectra (Stabenau and Zika 2004). The mixture is often characterized by its exponential increase in absorbance with decreasing wavelength (Green and Blough 1994, Kuwahara, et al. 2000). A simple exponential equation:

$$a_{\lambda} = a_{\lambda o} \exp(-S(\lambda - \lambda_o))$$

where $a_{\lambda o}$ is the absorption coefficient at λ_o (i.e., 290 nm) and S is the spectral slope coefficient, is used to fit measured light absorbance data, allowing differentiation between classes of CDOM by differences in S (Blough and Green 1994). It has been shown (Otis, et al. 2004) that $a_{\lambda,\mathrm{CDOM}}$ dominates the total attenuation of light below 500 nm near a CREWS station at Lee Stocking Island, Bahamas. Since the diffuse attenuation coefficient (Kd) is dominated by absorbance from CDOM at these wavelengths, it is expected that the wavelength dependence of Kd will show an exponential increase with decreasing wavelength, similar to that observed for CDOM. The diffuse attenuation spectral slope coefficient (S_{Kd}), can be used to describe this behavior and subsequently to predict the spectra and intensity at any depth within the well mixed waters found near the CREWS station.

One complexity in the determination of Kd from the CREWS data is the necessity for two in-water irradiance values from different depths. The CREWS station typically employs only a single in-water and a single above-water irradiance sensor. To determine Kd, the above water sensor data is corrected for reflective losses and refractive differences at the sea surface to produce theoretical irradiance values for a subsurface, z = -0 m, depth. Once the corrections have been performed, the subsurface values and measured in-water values are used to calculate Kd at the measured wavelengths (305, 330, 380 nm and a broadband measure of PAR). The S_{Kd} value is then calculated to allow interpolation between these measured wavelengths in order to determine the total wavelength dependent Kd. This value is applied to standard surface spectra to correct for in-water attenuation, valid for CDOM and other absorptive features for the specific hour the data were collected, and used to predict in near real-time the spectra and intensity of light at the coral surface.

An inherent feature of this approach is that variations in S_{Kd} are related to variations in the type and processing history of CDOM, which in coastal zones is closely coupled to variations in biota, including seagrass communities and surface water run-off (Stabenau, et al. 2004). Variations in CDOM type or concentration may indicate normal seasonal changes in these communities or may indicate long term ecosystem changes, due to either natural or anthropogenic causes. Thus, one achievement of CREWS station long term monitoring via the methods described here may be the elucidation of the causes and implications of variation in the shading properties of CDOM on coral health.

8.1.3. *Fluorescence Efficiency*

Previous studies have shown reduction in coral fluorescent yield as a coral stress response to, for example, high sea temperature (Jones, et al. 2000) or exposure to intense UVR (Jones and Hoegh-Guldberg 2001). This reduction in fluorescent yield typically precedes either mild or extensive coral bleaching, including the expulsion of zooxanthellae from the coral host. Variation in fluorescent yield during a diurnal cycle is larger than the night-to-night, dark-adapted variation in efficiency observed over time. Monitoring of the nighttime fluorescence yield of corals provides an early indication of the onset of coral bleaching, prior to when subjective determination of changes in the corals' color can be observed. For this reason, select CREWS stations have been designed to incorporate a direct measure of fluorescent yield to provide better coral bleaching predictions. Long term monitoring of fluorescence yield provides an additional baseline from which the expert system software can calculate deviation and determine significance.

The typical method for determining fluorescent yield is via pulse amplitude modulation (PAM) fluorometry. PAM fluorometers have been used at individual locations and with variable sampling intervals to determine photosynthetic health, both for terrestrial plants and, more recently, for submerged vegetation and corals (for a review, see Fitt et al. 2001). The next generation PAM fluorometer, a multi-sensor "monitoring PAM" designed for long-term underwater deployments, has been incorporated into the CREWS station architecture (see Figures 6-8). Typical PAM fluorometry output data (Figure 9) provide the dark adapted background fluorescence (F_0) and the maximum fluorescence observed when the coral is exposed briefly to a saturating pulse of broad spectrum light (F_m). The instrument then calculates the variation in fluorescence ($F_v = (F_m - F_0)/F_m$) which is the fluorescent yield. In a monitoring PAM deployment, the time series data will show very low values of F_v during the day since the corals undergo dynamic photoinhibition, essentially eliminating a portion of the excess light energy from photosystem II for protection from cellular damage (Lesser and Gorbunov 2001). However, in the nighttime hours (a subjective period recognized by the expert system software, cf. Table 2), the F_v values quickly rise to a stable range, with healthy corals achieving values as high as 0.65. Higher values are exhibited in conditions favorable for coral growth, while lower values are observed when corals are stressed. Subjective data ranges are applied to these values to allow expert system-based early warnings of coral bleaching events.

The decision table utilizing the abbreviations and subjective ranges shown in Table 2 may be seen in Table 3 as an example for use of these data to predict coral bleaching. The monitoring and information architecture, therefore, not only models conditions conducive to coral bleaching, but also reports when the coral is actually undergoing physiological stress consistent with coral bleaching. Such output is of value not only to coral researchers seeking to understand the environmental stressors and physiological mechanisms associated with bleaching, but also to MPA managers who wish to directly assess the status of a species of coral being monitored.

Deployment of a monitoring PAM fluorometer requires special consideration. Since it is an optical instrument utilizing a light source, it needs to be frequently cleaned because of the detrimental affect of biofouling organisms. Unfortunately, anti-fouling options are potentially harmful to the corals being monitored and, at the time of this publication, a successful mechanism for the automated cleaning or protection of optical interfaces has yet to be developed. Here again, high quality and intense *in situ* monitoring requires an attentive station maintenance plan attuned to output from the CREWS software and a regular station maintenance schedule. Fortunately, the lens itself is a polycarbonate material and apparently has similar resistance to biofouling as has been observed with Teflon™ coatings on irradiance sensors. These coatings exhibit fairly low rates of biofouling because the non-porous material isn't easily colonized, or adhered to, by biofouling organisms in the marine environment.

In certain applications, the target corals may be some distance from the CREWS station. However, utilization of the monitoring PAM fluorometer is still possible, with communication to the tower achieved through use of acoustic modem technology (Figure 10), currently under development at AOML. Acoustic modems transfer data underwater acoustically, rather than through the use of cables, satellite or radio transmission, as do aerial data transmission modes. AOML's Telemetered Instrument Array (TIA) architecture consists of a receiving acoustic modem on the CREWS station, and a sending acoustic modem on a special remote instrumented array. The TIA is capable of physically supporting and combining the signals from a monitoring PAM fluorometer, a Conductivity-Temperature-Depth (CTD) instrument, an irradiance spectrophotometer, and a transmissometer. Data are acquired from each of these instruments, averaged over a period of one hour, and then sent as a composite data stream to the receiving modem on the CREWS station. All data parameters from the station are then combined for transmission to the GOES satellite in the usual fashion. The flexibility of combining multiple instruments at great ranges from the station, with data collection and delivery in near-real time at the station, greatly expands the possibilities for support of *in situ* coral research since different needs and different researchers may be accommodated.

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Table 1. Phases and tasks in CREWS station construction and deployment.

Site Selection
- Host Site Discussions
- Organize Travel
- Dive Plan Instituted
- Travel to Host Region
- Boat Trip to Candidate Sites
- Record and Discuss Sites
- Return to AOML

Permitting
- Discover Permitting Agency
- Acquire Permit Application
- Submit Permit Application
- Receive All Permits

Purchasing
- Permit Fee(s)
- Electronics Infrastructure
- Instrumentation
- Pylon Materials
- Tools
- Contractor
- Rentals
- Other Fees
- Freight
- Boat Rentals
- Diving Gear
- Drilling Gear
- Software
- Computer Hardware
- Bottom Plate Materials
- Purchase Delivery Trailer

Pylon Construction
- Custom Fabrications
- Custom Assemblies

Electronics Assembly
- Data Logger
- GOES Transmitter
- Power Supply Assembly
- Custom Cable Assembly
- Instrument Interfacing

Testing at AOML
- Electronics Tests—AOML
- Electronics Tests--Hatchery Tanks

Bottom Plate Delivery
- Arrange Shipping
- Deliver Plate and Drilling to Shipper
- Arrange for Receiver at Site
- Storage at Site

Bottom Plate Installation
- Organize Travel
- Rent or Arrange Boat
- Travel to Site
- Deliver Plate and Drilling to Boat
- Install Plate
- Review Installation
- Return to AOML

Pylon Packaging
- Rent or Arrange Lifting Gear
- Package for Shipment
- Deliver to Shipper

Pylon Delivery
- Receive Pylon at Site
- Move to Close Harbor
- Transfer to Boat or Ship
- Pylon Pre-Assembly
- Electronics Packaging
- Pack for Shipping

Electronics Delivery
- Move to Shipper
- Station Pre-Installation Assembly

Pylon Installation
- Arrange Travel
- Organize Employee Schedules
- Travel To Host City
- Meet with Host Support
- Travel to Installation Site

Install Pylon
- Electronics Pre-Installation Assembly
- Electronic Infrastructure

Electronics Installation
- Install Electronics at Site

Field Electronics Testing
- Test Configuration
- Feedback from AOML
- Finalize and Return Home

Figure 1. A CREWS Station near the Caribbean Marine Research Center, Lee Stocking Island, Exuma Cays, Bahamas.

Figure 2. Sequence of events in the planning of installation of a CREWS station.

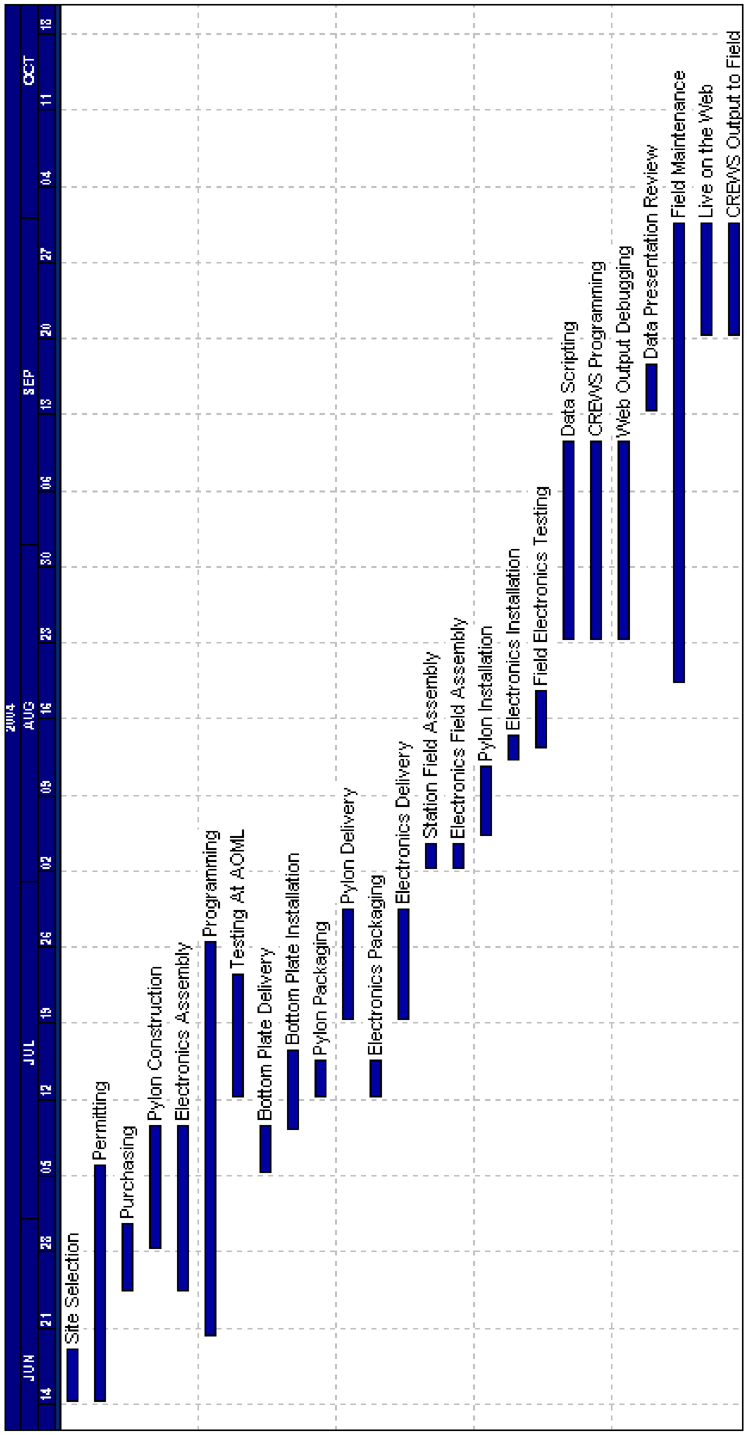

Figure 3. CREWS Web underwater camera architecture. Real-time video is sent from an underwater camera through a microwave transmitter on the CREWS station to a receiver on land, then through an encoder, then finally over a secure service-net to a central Web server where they are broacast over the Internet.

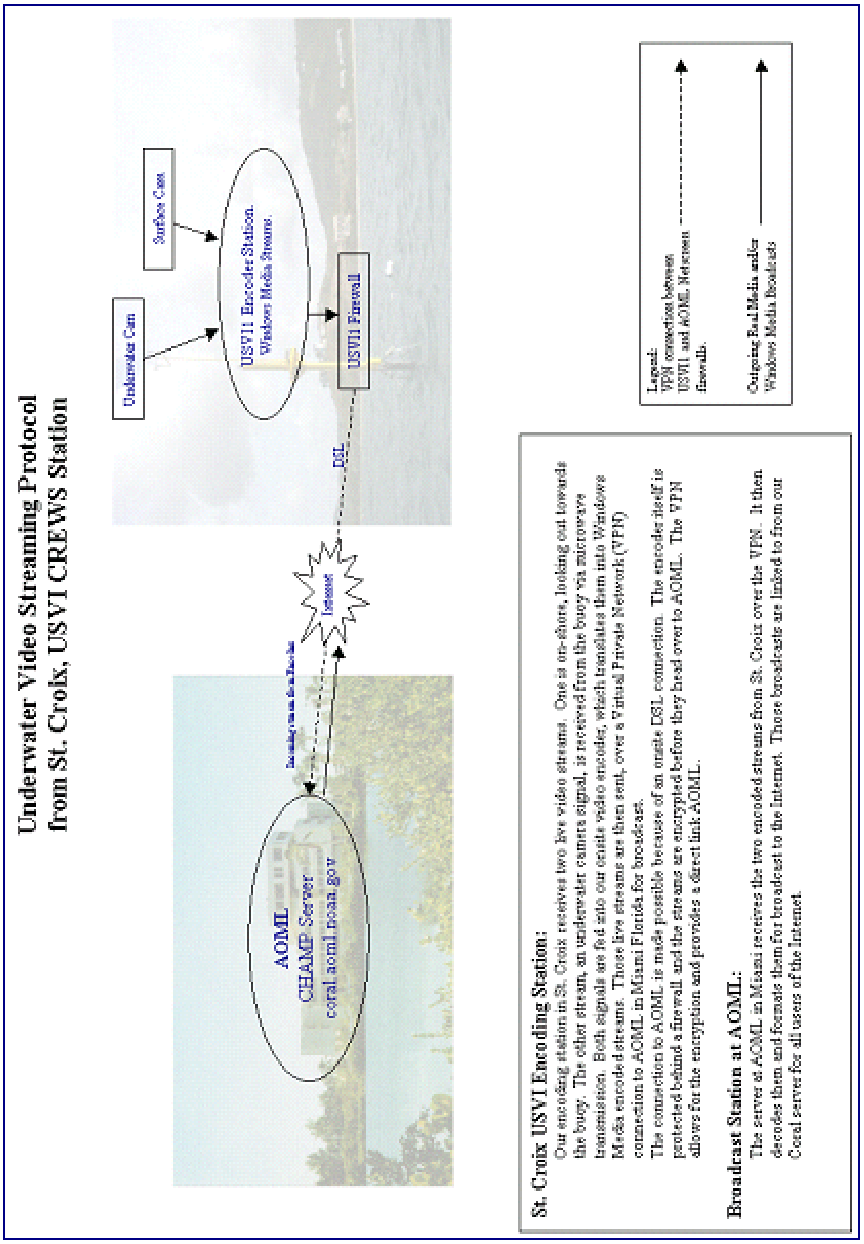

Figure 4. Flow of data from the CREWS station to the various destinations.

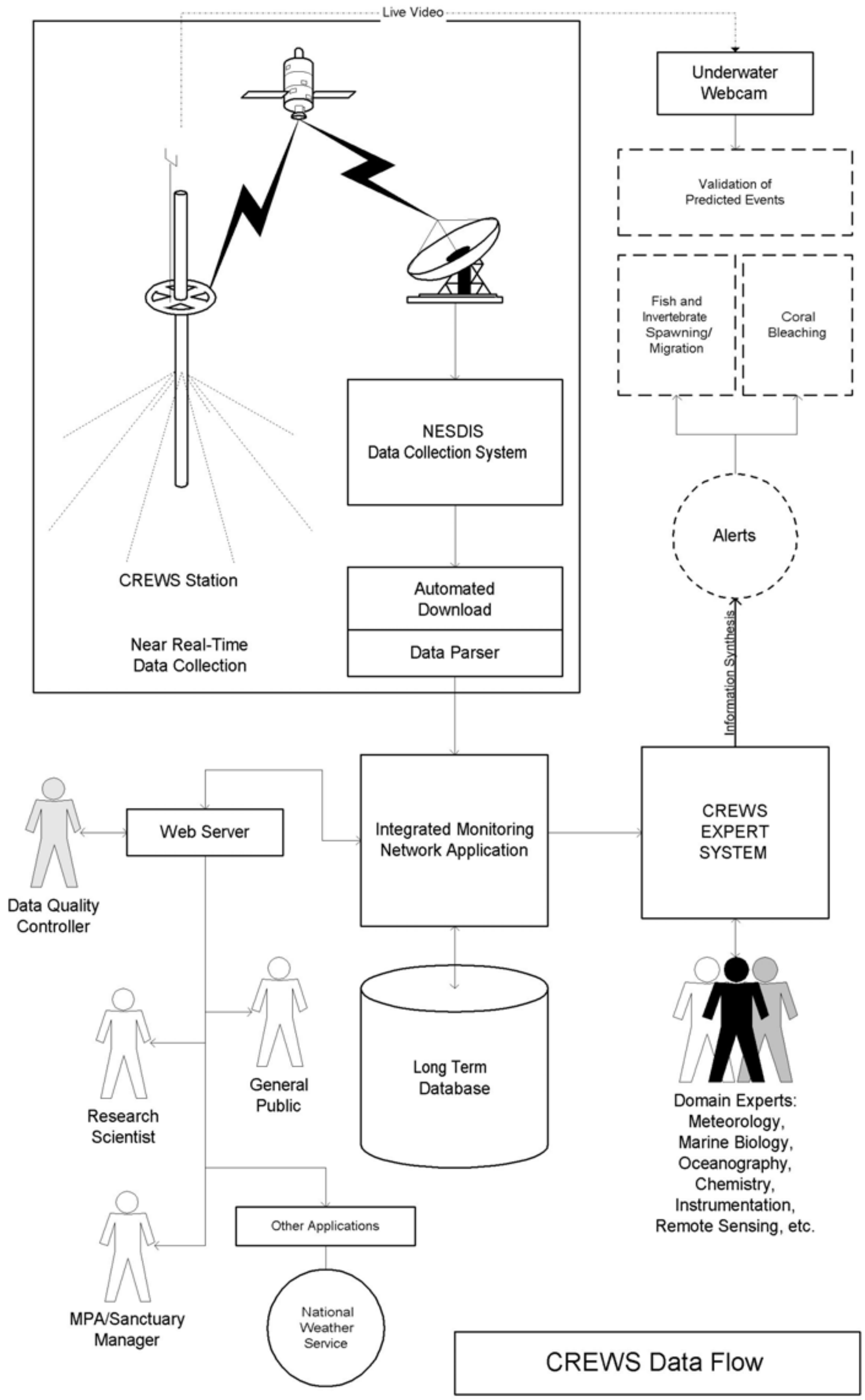

Figure 5. An example interface from Integrated Monitoring Network, which collects data from the CREWS and SEAKEYS networks.

Table 2. Local time periods are subjectively grouped for use by the expert system software to allow the automated interpretation of data with respect to easily understood diurnal periods. If the conditions characterized in the subjective data ranges (e.g., “somewhat low”) hold for beyond one or more of the Basic Periods, they are recategorized into the next Longer Period (e.g., “daylight-hours”). See Table 3 for the next step in processing.

Subjective Data Ranges:

Abbreviation	Descriptor	Abbreviation	Descriptor
ul	unbelievably low	sh	somewhat high
dl	drastically low	hi	high
vl	very low	vh	very high
lo	low	dh	drastically high
sl	somewhat low	uh	unbelievably high
av	average		

Subjective Periods of the Day:

Abbreviation	Period	Local Time
(Basic Periods)		
midn	midnight	2200 - 0100
pdaw	pre-dawn	0100 - 0400
dawn	dawn	0400 - 0700
morn	morning	0700 - 1000
midd	mid-day	1000 - 1300
psun	pre-sunset	1300 - 1600
suns	sunset	1600 - 1900
even	evening	1900 - 2200
(Larger Groupings)		
all	all-day	2200 - 2200
dayl	daylight-hours	0400 - 1900
nite	night-hours	1900 - 0400
dayb	dawn-morning	0400 - 1000
aftn	afternoon	1300 - 1900

Table 3. Expert software system decision table, set at initial conditions based on the study herein, used to provide reports on the probability of a coral bleaching event based on combinations of environmental conditions and coral photosynthetic health indicators in specific time intervals. Conditions monitored include Fv (unitless ratio of coral fluorescence at rest and under intense light), Ed_λ (wavelength specific downwelling irradiance, uW cm^-2 s^-1) at the coral surface, and sea surface temperature.

Rule: High Sea Temp + Low Fluoro Yield (night) + High Noon Irradiance + Low Winds
(Julian Day: 172 to 264...Season: Summer)

		ul	dl	vl	lo	sl	av	sh	hi	vh	dh	uh
IF	sea temp									all (24) dayl (15) nite (9) dayb (6) aft (6) basic (3)	all (48) dayl (30) nite (18) dayb (12) aft (12) basic (6)	
and:	fluor yield		nite (18)	nite (9)	nite (6)							
and:	irradiance									mid (6)	mid (12)	
and:	wind speed		all (24) dayl (15) nite (9) dayb (6) aft (6) basic (3)	all (24) dayl (15) nite (9) dayb (6) aft (6) basic (3)								

THEN

Conditions are [probably/possibly] conducive to mass coral bleaching.

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See Table 2 for day-period designations.

Note: The expert system adds up all the points in parentheses for conditions that hold, then outputs an "alert" which shows totals for each parameter, as well as a combined total. The total number of points act as an environmental index of stress that results in coral bleaching.

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KEY: Subjective assignments for fluorescence yield and maximum noon insolation.
(Note: These are starting levels yet to be verified through lab and field experimentation.)

	Fv		Ed
dl	.30 - .40	uh	> 1000
vl	.40 - .55	dh	800 - 1000
lo	.55 - .65	vh	600 - 800
uh	> .80		

Figure 6. Power from the central CREWS station is supplied to the central canister of the PAM fluorometer (see text for further explanation). Here a diver unravels the four cables from the central canister which lead to the individial monitoring PAM sensors, which will be applied to four different species of corals.

Figure 7. Divers position one of the monitoring PAM sensors at one of the species (*Agaricia agaricites*) to be monitored.

Figure 8. A diver must position the monitoring PAM sensor head precisely over the coral species in question (here, *Siderastrea siderea*) using a pre-measured spacing tool.

Figure 9. Diurnal cycle observed from multiple detectors of a monitoring pulse amplitude modulating (PAM) fluorometer deployed at Lee Stocking Island, Bahamas, 2005. Decrease in nighttime fluorescent yield would be expected when corals are experiencing thermal or photochemical stress (not indicated here). Separation of the signal into subjective day and night periods is necessary to interpret long term trends.

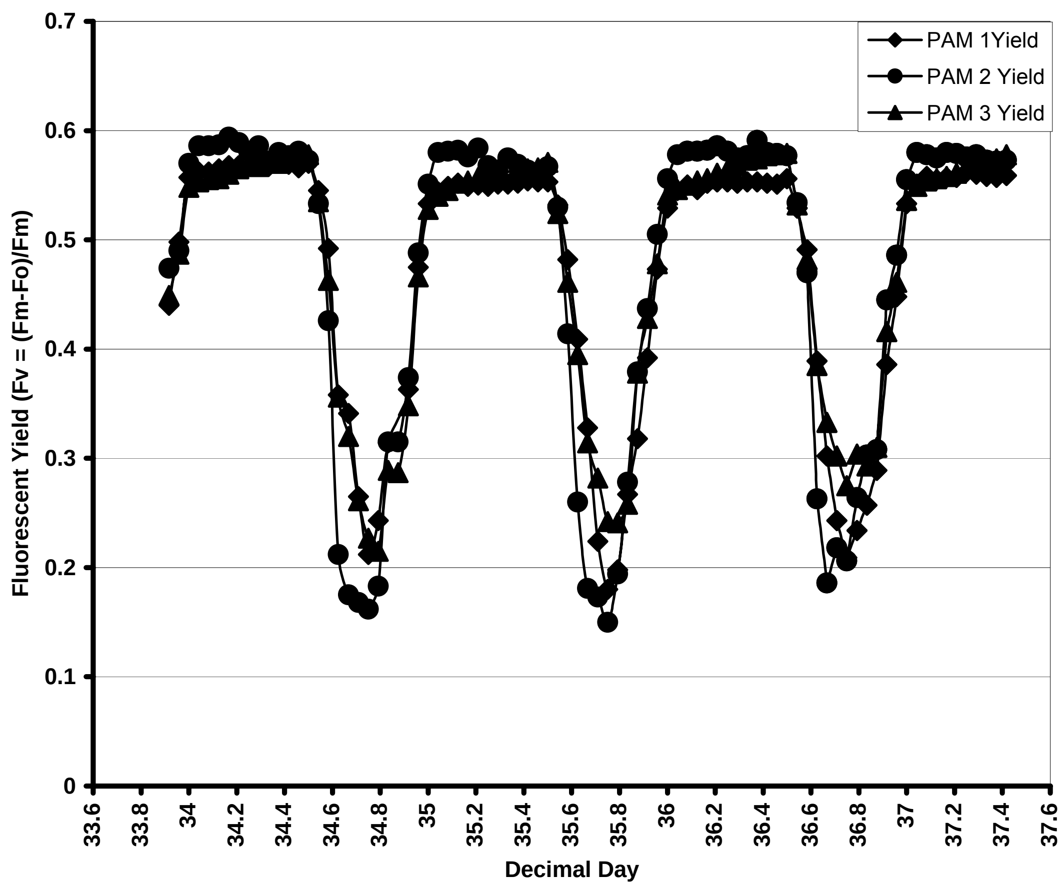

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Figure 10. Envisioned deployment of a Telemetered Instrument Array, containing a monitoringPAM fluorometer, a CTD instrument, a transmissometer, an irradiance spectrophotometer, and a transmitting modem, in the vicinity of a CREWS station with a receiving acoustic modem for acquiring data remote from the station. See text for details.